# GENERAL COMMENTS ON GAC DESIGN ISSUES EMBODIED IN THE ADMINISTRATIVE ORDER

Environmental Research & Technology, Inc.
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## Introduction

The Administrative Order specifies detailed design criteria for a GAC system (Exhibit C). These design criteria provide specifications in two seperate areas: 1) the performance requirements of the system and 2) the specific design to be utilized in meeting the performance requirements. The key issues raised by the design criteria are:

- the legitimacy of ordering a specific design as opposed to performance requirements alone;
- the legitimacy and accuracy of the performance requirements, including the design bases;
- the legitimacy of the specified design, as opposed to alternate designs;
- the cost implications of different designs; and
- the cost implications of different criteria.

Each of these issues is addressed below.

## Specifying Performance vs. Design

The two basic approaches to an engineering contract are to specify basic performance requirements, or to specify the actual equipment design. The latter is done in instances where there are specific design constraints on compatibility, operation, proprietary technology, etc. The Administrative Order specifies equipment design (Exhibit C), apparently on the basis that a specific design of known feasibility and reliability is required to protect public health.

However the feasibility and reliability of the CH2M Hill design, which is the basis for the Administrative Order's design requirements, are not "known" because the design is based solely on limited pilot testing. Instead the design reflects a considerable degree of CH2M Hill's professional engineering judgment (presumably with input from EPA and MPCA, and perhaps that of SLP). Without questioning CH2M Hill's credentials, it is possible that different designs may also provide acceptable feasibility and reliability. Moreover, other designs may be less costly, and hence more "cost-effective" by CERCLA criteria. Specific comments on an alternate design proposed by Calgon Corp. and its feasibility, reliability and cost implications are provided later in these comments.

## Performance Requirements

The performance requirements specified in the Administrative Order (Exhibit C) are 1) 1,200 gpm flow rate and 2) treated water quality to be 2.8 ng/l carcinogence PAH and 280 ng/l total PAH. A design basis of 7,000 ng/l total PAH in the raw water is also noted. An additional important design basis not addressed by the Administrative Order (nor the ROD) is the location of the GAC system relative to the existing sand filters.

### Flow Rate

The 1,200 gpm flow rate is correct for the system capacity. However, this should not be the operating rate for the system. Prior to their closure, wells SLP10 and 15 operated at a combined annual average rate (1972-77) of about 300 million gallons per year (570 gpm - see Appendix G, Table G2-2 in ERT's April 1983 report). In practice, this reflects operation of the wells in a pattern of alternately running "full bore" (about 1200 gpm) or not running at all, depending on time of day and season. There is no reason to require 1,200 gpm operation continuously year-round, as implied by the ROD (pg. 9) or as assumed by CH2M Hill's cost estimates (Tech Memo K, pp. 19 & 20). Our modeling of gradient control well systems in the

Prairie du Chien-Jordan was based on 300 MGY pumpage and showed this to be adequate. Higher rates are therefore unnecessary to meet the ROD's gradient control objectives, will add considerable cost (O&M cost is roughly proportional to total flow), and will pose unnecessary (and probably unwanted) constraints on the city's operations of its water supply system. It is even possible that the city will have no way to use 1,200 gpm of water produced during low demand periods (e.g., night-time during the winter).

Given the above, the design basis should be clearly stated as 1,200 gpm system capacity, but the operating rate should be left to the city. It would be reasonable to set some minimum requirement on pumping rates to ensure some gradient control benefits, but further input would be required from the city to set these requirements in a reasonable manner. An example approach would be 250 million gallons minimum annual pumpage and 20 million gallons minimum in any one month.

Criteria

The criteria are the key performance requirements. As indicated in our other comments, we disagree with the 2.8/280 criteria. These criteria also have significant cost, feasibility and reliability implications, as discussed later.

Raw Water Quality

The Order should make it clear that the raw water quality is given as a design basis, not as a performance requirement. In other words, the treated effluent criteria should be met regardless of the raw water quality.

The value of 7,000 ng/l total PAH in the raw water given in the Administrative Order (Exhibit C) and used in CH2M Hill's design and costing (Tech Memos K and O/P) is questionable. Using CH2M Hill's data for the specific PAH compounds listed by the Administrative Order

(Exhibit E) gives a total PAH concentration of about 12,000 ng/l.* These different feed concentrations result in significant differences in calculating O&M costs, as described later.

Sand Filter Effects

The Administrative Order and ROD do not say whether the GAC system should be upstream or downstream of the sand filters. CH2M Hill's design is based on an upstream location.

Calgon and ERT feel strongly that locating a GAC system upstream of the sand filters is likely to incur operating problems and is contrary to standard water treatment practice. The upstream location could lead to reduced carbon life or pluggage by the effects of well sand and iron deposits and the resulting need for more frequent backwashing, which abrades the carbon.

Specified And Alternate Designs

The CH2M Hill design, which is reflectd in the Administrative Order's requirements in Exhibit C, is based on three columns piped in such a fashion that they can be operated in series or in parallel or in some combination (e.g., two in series with one follow-up unit). The key requirement is that the columns can be operated in series, which is apparently the intended configuration. The primary basis for this appears to be a desire to minimize any chance of treated water which exceeds the criteria from entering the distribution system (see, for examples, pp. 11 and 12 in the ROD and CH2M Hill Tech Memos K and O/P). Once a design objective of columns in series is established, the column sizes and system capital cost are pretty much established by hydraulic limitations and carbon performance. In this case, the result is three, rather unusually-sized, short, fat columns (16 ft. diameter by 5 ft. high), which would need to be custom built.

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*CH2M Hill results for seven wellhead and drum samples from SLP15 analyzed during their bench testing work give 11,000 ± 400 ng/l (Tech Memo H) and for nine wellhead samples during their pilot testing give 12,600 ± 600 ng/l (Tech Memo K).

Calgon prepared a report for ERT last fall on an alternate design using standard size, "off-the-shelf" columns (10 ft. diameter by 14 ft. high). Hydraulic limitations would require two such columns in parallel. The resulting carbon volume would give carbon utilization and performance closely comparable to the CH2M Hill design.

Ignoring cost considerations for the moment (which are discussed later), the fundamental difference between the Calgon and CH2M Hill designs is one of design philosophy with respect to safety and "fail-safe" performance. Both designs should meet the performance criteria.* The question is how much safety is required in preventing treated water that exceeds the criteria from entering the distribution system.

We believe that CH2M Hill's design is unnecessarily conservative. Moreover, we believe it is over-conservative to the point of not being cost effective compared to Calgon's alternative design, since the former may require as much as almost $0.5 million in additional capital cost compared to the latter (see discussion below).

The following points demonstrate that Calgon's design should provide an adequate margin of safety in the GAC system operation:

1) The alleged adverse health effects of PAH are exhibited under chronic exposures. Exceeding the criteria on a short-term, temporary basis will not pose "imminent and substantial endangerment" to public health.

2) A considerable margin of safety is provided by the fact that there are other wells and a storage tank at SLP Station No. 1 (where SLP10 and 15 are located). The criteria will presumably be applied to the GAC effluent (the Administrative Order should be more explicit on the point where the criteria apply), and if SLP3 and SLP11 together are run at a comparable

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*Assuming that quinoline is not required to meet a 2.8 ng/l criterion. See discussion later in these comments.

rate to SLP10 and 15, there will be roughly two-fold dilution of any GAC effluent entering the distribution system.

3) The GAC system is expected to have a very long carbon life, on the order of 2 to 3 years. The monitoring schedule proposed (monthly during the first two carbon cycles and quarterly thereafter - see Exhibit D Section 2) should give adequate warning of impending breakthrough (i.e., effluent exceeding the criteria) given this long carbon life, particularly after some operating experience is gained.

4) The carbon can be changed quickly once breakthrough occurs or approaches. Given a few days notice, a load of new carbon can be delivered and replaced in a day or two. Hence, breakthrough should not seriously upset the overall operation of the SLP water supply system.

5) Calgon reports that they have specified similar designs (parallel columns with no backup series column) at other drinking water applications, including some Superfund sites, and that these have performed well.

Cost Implications of Different Designs

In their September, 1984 report to us, Calgon provides rough cost estimates (±30%) for the CH2M Hill design and Calgon's alternate design. There is a lot of detail involved in comparing the various cost estimates that have been made by Calgon, CH2M Hill and the ROD. It is important to discuss some of these details, however, in order to understand the basis for the widely divergent cost estimates that have been reported and the effects of the treatment criteria on costs.

It must be noted that all of the costs discussed below are based on the EPA's criteria of 2.8/280 assuming that quinoline is not counted as a carcinogen.*

*All of the cost estimates also apply to the case of 28/280 as criteria when quinoline is counted as a carcinogen.

The effects of different criteria and different treatment of quinoline are discussed in the final section of these comments.

Capital Costs

Calgon's capital cost estimates are compared below with those of the ROD and CH2M Hill:

| Design | Capital Cost Estimate, $1,000's Calgon | ROD | CH2M Hill |
|---|---|---|---|
| CH2M Hill | 964 | 750 | 696 |
| Calgon | 501 | - | - |

Two important points are clear from this comparison: 1) the Calgon design is much less expensive than the CH2M Hill design when compared on an equivalent basis ($500K vs. $964K) and 2) CH2M Hill's and the ROD's costs may be significantly underestimated ($750K vs. $964K). Note, however, that all of these estimates are only acurate to 25 or 30%. Better accuracy would require detailed designs, which are not available at present.

There are a number of important details underlying these estimates. First, CH2M Hill estimated costs for desanding SLP10 and making it serviceable again ($65,000). We have not included this in their estimate, since we believe that SLP should legitimately bear this cost. The ROD did not count this cost either (see 5/22/84 Riner/Bitter phone memo). The ROD does include $49,000 for replumbing the treatment system at SLP Station No. 1 to hook up wells SLP10 and SLP15. Calgon also included this cost (estimated at $36,000), but it is unclear if CH2M Hill did.

Second, Calgon's cost is based on housing the GAC system in a building of comparable quality to that existing at SLP Station 1. This seems reasonable, particularly given the climate and the residential neighborhood. CH2M Hill's design had insulated columns located outside, which would be unattractive in a residential area and could pose serious operating problems during the winter (e.g., sample line freeze-up).

Third, none of the estimates includes the cost of a booster pump, although two are likely to be required (one spare) - for either design - by the additional pressure drop resulting from the carbon beds. This would add roughly $50,000 to the capital cost.

Finally, all of the estimates include costs for pilot columns (about $8,000). These are not necessary to the operation of the GAC system and are included solely to help in subsequent evaluation of alternate carbons (see CH2M Hill Tech Memo K). This item should be left to the judgement of SLP and Reilly and not specified by the Order.

Operating Costs

Operating costs estimated by Calgon, CH2M Hill and the ROD are compared below:

| | O&M Cost Estimates $/Year | | |
|---|---|---|---|
| Design | Calgon | ROD | CH2M Hill |
| CH2M Hill | 30,000 | 188,000 | 132,000 - 206,000 |
| Calgon | 29,000 | - | - |

The two key points here are 1) Calgon says that the Calgon and CH2M Hill designs should have closely comparable O&M costs (they can be considered equivalent within the accuracy of the estimates), and 2) the O&M costs estimated by CH2M Hill and the ROD are far higher than Calgon's estimates. Again, all of the cost estimates are only accurate to about 30%. Moreover, there are a lot of details that affect comparisons. The more important details are discussed below.

Calgon's cost estimates do not include monitoring costs. CH2M Hill and the ROD do include these costs at $19,000/year. We have earlier estimated monitoring costs under our proposed scheme at

$5,700/year for the first six years and $3,000/year thereafter. In April 1984, St. Louis Park estimated monitoring costs of $19,000 in the first year, $8,000/year for the next five years, and $3,000/year thereafter. These estimates were reviewed by the MPCA. There is obviously basic agreement here in the long term, but some minor details to work out for near-term monitoring.

The CH2M Hill and ROD cost estimates include significant costs for operating SLP10 and 15, even though this is a cost that should be borne by the city, since they would pay it even if the wells were not contaminated. At least $13,000 is included in this category, plus a large but unknown fraction (approaching 100%) of the $46,600/year in electrical costs, which are mainly for running the pumps (see CH2M Hill Tech Memo K). All told, these account for about $55,000/year in the EPA's estimates.

Dropping the monitoring and SLP10/15 well operating costs from the ROD and CH2M Hill estimates yields the following comparisons:

| | O&M Cost Estimates, $/Year | | |
|---|---|---|---|
| Design | Calgon | ROD* | CH2M Hill* |
| CH2M Hill | 30,000 | 114,000 | 58,000 - 132,000 |
| Calgon | 29,000 | - | - |

The ROD and CH2M Hill cost estimates are significantly lower than before, but still much higher than Calgon's. This difference reflects two major areas. First, Calgon has much lower estimates for maintenance, labor and utilities ($15,000 to $20,000/year) compared to CH2M Hill and the ROD ($38,600/year). We believe that Calgon's experience supports their estimates as being more realistic. Moreover, we believe that the MPCA basically agrees with this (see below).

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*Original estimate less $19,000 for monitoring, $3,000 for fluoride, $10,00 for pump station labor, and $42,000 for electrical.

Second, Calgon has estimated much lower carbon costs ($13,500 to $9,000/year) vs. the ROD ($74,000/year) or CH2M Hill ($18,400 to $92,000/year). These differences reflect different assumptions in three areas: 1) operating rates (Calgon at 570 gpm vs. CH2M Hill at 1200 gpm), 2) raw water concentrations (Calgon at 13,000 ng/l vs. CH2M Hill at 7,000 ng/l total PAH), and 3) carbon capacities and breakthrough times. The first two items just about cancel each other (Calgon only treats 48% as much water, but assume 86% more PAH, for a net effect of only 11% difference in the PAH loading - with Calgon's being lower). The carbon life is the major source of the cost differences. Unfortunately, no one knows how long the carbon will last in this system. The test data to predict this reliably just do not exist. Any life estimate is an educated guess. This problem does not affect the capital cost estimates, but does have a major bearing on the O&M costs.

The question of carbon life estimates is reserved for the final section of these comments as part of the discussion on the implications of different criteria. For now, let it suffice to say that we believe that the MPCA and EPA would agree that Calgon's cost estimates are more realistic than CH2M Hill's. For example, the city's cost estimates of April 1984, which were reviewed by the MPCA, used an O&M cost of $33,000/year (excluding monitoring). This was also the estimate used by the MPCA during our meetings in January. It should also be noted that disagreements over O&M cost estimates have no relation to whether or not CH2M Hill's or Calgon's design will achieve the treated water PAH criteria (barring the problem of quinoline discussed below). Such estimates are important, however, in determining the cost-effectiveness of alternate designs and alternate PAH criteria.

## Cost Implications of Different Criteria

There are three issues regarding effluent criteria that could affect GAC costs: 1) the criterion for noncarcinogens, 2) the criterion for carcinogens, and 3) the treatment of quinoline. These are discussed below in reverse order as listed here.

## Treatment of Quinoline

Whether or not quinoline is treated as a carcinogenic PAH that will have to meet a criterion of 2.8 ng/l could have a major effect on the cost of GAC treatment, and possibly its feasibility. Quinoline is present in SLP15 raw water at about 10 ng/l*. It is not certain that Calgon's or CH2M Hill's design can ensure removal of quinolne to below 2.8 ng/l. There is no isotherm data available for quinoline in CH2M Hill's work or in the open literature that we can find. It is suspected to have relatively poor adsorption properties. During CH2M Hill's pilot test, it was detected in 17 of 26 effluent samples at 1.0 to 4.4 ng/l (2.0 ng/l average), with 9 not detectable results. This is sufficiently close to the 2.8 ng/l criterion that it is uncertain if a full-scale system would meet this criterion for quinoline. This would depend in large part on the monitoring protocols and the analytical laboratory, as well as the system's true performance.

If quinoline can indeed be removed to less than 2.8 ng/l by a full-scale system, it is not known how long this performance could be achieved (i.e., what carbon life would be achieved). There is an approach, however, that can be used to estimate roughly the carbon life that could be attained. This approach is described below:

Take the case of the Calgon design with two parallel beds containing 9 feet of carbon. The bottom 3 feet is taken to be the mass transfer zone (MTZ) (maxmimum length estimated from CH2M Hill's work as described in Calgon's report). In the 6 feet above the MTZ, it is assumed that the carbon will achieve the adsorption capacity for any given constituent, including quinoline. In the MTZ, the breakthrough time (and adsorption capacity) depends on the constitutent's particular mass transfer kinetics. Adsorption

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*Only CH2M Hill has analyzed for quinoline. Many times it was not detected at a detection limit of 10 ng/l. On other occasions, it showed up at 11-13 ng/l.

capacities can be obtained from CH2M Hill's isotherm data. Mass transfer kinetics must be obtained from long-term tests, but in some cases CH2M Hill's 42-day pilot test does provide some tenative data on mass transfer kinetics.

For the case of quinoline, there are no isotherm data from CH2M Hill's work because all feed and treated samples gave results below the detection limit. However, there are two approaches for crudely estimating an adsorption capacity for quinoline. First, plotting adsorption capacities (X/M - ng of X removed per mg of carbon) at a residual concentration of 10 ng/l (the approximate feed concentration for quinoline) versus the octanol-water partition coefficient for a series of PAH tested by CH2M Hill gives a reasonable correlation, with log (X/M) increasing linearly with log (Kow). This includes data for two larger heterocyclic compounds (acridine and carbazole). The data span a range of 2 to 200 ng/mg for X/M and 3 to 5 for log Kow. Extrapolating these data yields an X/M of 0.2 to 1.0 ng/mg for quinoline based on its reported log Kow of about 2.05.

The second approach uses the average effluent concentration from the first 3-foot column of CH2M Hill's pilot test (1.3 ng/l), an influent concentration of 10 ng/l (assumed), a 38-day test period (to allow for line-out) and a carbon mass of 3500 grams to calculate an X/M value of 0.23 ng/mg, which is in good agreement with the first approach.

Using a feed concentration of 10 ng/l, a flow rate of 300 MGY, 26,700 pounds of carbon (6/9 of 40,000 pounds), and an adsorption capacity of 0.2 to 1.0 ng/mg, one can calculate a time of from 80 to 390 days to exhaust the quinoline adsorption capacity of the top 6 feet of the carbon. For the bottom 3 feet, we estimate 60 days for breakthrough, based on linear extrapolation of CH2M Hill's 42-day test data for their first 3-foot column (a linear regression of these data is significant at the 99% confidence level with a slope of 0.04 $\pm$ 0.01 ng/l/day [mean $\pm$ standard deviation]). Hence, the carbon life dictated by a 2.8 ng/l criterion for quinoline would be 140 to 450 days, or 0.4 to 1.2 years. This gives an annual carbon cost of

$33,000 to $100,000 per year for Calgon's design. A similar approach for CH2M Hill's design (three beds in series with a 3-foot MTZ and 10.5 feet total carbon bed length) gives a life of 0.5 to 1.9 years for an annual carbon cost of $32,000 to $120,000 per year.

It must be stressed that these are all very crude calculations involving rather bold assumptions and extrapolations. Nonetheless, we believe they give the best sense possible from the available data of quinoline's effects on carbon life with a 2.8 ng/l criterion.

At a carcinogenic PAH criterion of 2.8 ng/l, then, there is a distinct possibility that treating quinoline as a carcinogen would 1) make GAC treatment infeasible or 2) make the operating costs excessive (doubled to quintupled or more). However, it is also possible that neither of these events would occur. Unfortunately, the data to predict one alternative or another definitively do not exist at present.

By contrast, at a criterion of 28 ng/l for carcinogens, the treatment of quinoline is probably irrelevant. Even if all of the quinoline breaks through, that would leave about 18 ng/l for other carcinogenic PAH. It is virtually certain that a criterion of 280 ng/l for noncarcinogens (or a comparable criterion) would be exceeded long before carcinogenic PAH other than quinolne exceeded 18 ng/l.* Hence, the importance of quinoline to the feasibility and cost of GAC treatment depends directly on the criterion for carcinogenic PAH.

## Carcinogen Criterion

A 28 ng/l criterion for carcinogens should not control the carbon life, and hence O&M cost, of a GAC treatment system at SLP15. The highest carcinogenic PAH concentrations, excluding quinoline, measured at SLP15 by GCMS are about 60 ng/l (see Monsanto test results in Appendix G of ERT's April 1983 report). CH2M Hill typically gives results in the range of 20 to 30 ng/l.

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*See next section.

During our February 1983 test at SLP 15, we measured 71 ± 54% removal of carcinogenic PAH across the sand filter (95% confidence interval). This indicates that the feed water to the GAC system should contain about 20 ng/l of carcinogenic PAH. Even with total breakthrough of these in the GAC system, which is extremely unlikely, a criterion of 28 ng/l would still probably be achieved, even counting quinoline as a carcinogen with total breakthrough at about 10 ng/l (which is likely to occur at some point during the carbon's life).

If a criterion of 2.8 ng/l is established for carcinogenic PAH, the treatment of quinoline will be the key issue affecting carbon life. As described above, if quinoline is treated as a carcinogen, this would probably reduce the carbon life substantially. If quinolne is not treated as a carcinogen (or has a separate criterion), then a 2.8 ng/l criterion for the other, higher molecular weight carcinogens should not control the carbon life. CH2M Hill's isotherm data, plus other results in the open literature, show that high molecular weight carcinogenic PAH have much stronger adsorption tendencies than the lower molecular weight noncarcinogens, so breakthrough is expected to occur for the latter first. CH2M Hill's pilot testing provides supporting evidence of this, in showing no higher molecular weight carcinogens in the effluent from the first 3 foot column at any time during their 42 day test. Calgon's report supports these conclusions on the effects of carcinogenic PAH criteria on GAC performance.

Nonarcarcinogen Criterion

As indicated in Calgon's report, CH2M Hill's pilot testing and isotherm data indicate that 2,3-dihydroindence (DHI) is the likely to be the first compound to break through above a 280 ng/l limit for noncarcinogens. Taking the same approach as described above for quinoline, we estimate a carbon life of 2.3 years for Calgon's design and 3.6 years for CH2M Hill's design, based on DHI controlling breakthrough at 280 ng/l*. These yield annual carbon costs of $17,200 for Calgon's design and $16,600 for CH2M Hill's design.**

Marginal increases in the noncarcinogen criterion will have very little effect on carbon life and cost. This is because DHI is present at about 1,900 ng/l in the feed, and will break through at this level versus 280 ng/l in an additional month or so. (This is a rough estimate from CH2M Hill's pilot testing breakthrough curve for DHI exiting the first 3-foot column).

A significant increase in carbon life will require raising the noncarcinogen criterion into the range of 1,000's of ng/l. For example, a criterion of 3,000 ng/l would give a carbon life in Calgon's design of about 3 years. This is based on summing the feed concentrations of the individual constitutents with predicted carbon lives of less than 3 years (i.e., DHI, indene, benzo(b) thiophene and 1-methylnaphthalene)***. This would reduce the annual carbon cost from $17,200 (based on DHI breakthrough at 280 ng/l) to $13,300. A similar reduction would occur for CH2M Hill's design. The next significant increase in carbon life (to somewhat over 4 years) would require a noncarcinogen criterion of about 6,000 ng/l (to allow for breakthrough of acenaphthene and acenaphthylene). This would drop the annual carbon costs by another $3,500 or so.

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*Based on feed concentration of 1,930 ng/l (average during CH2M Hill's 42-day test), X/M of about 350 ng/mg (from plotting CH2M Hill's isotherm data), and a 3-foot MTZ with about 70 days for DHI to break through at 120 ng/l (from extrapolating a semi-logarithmic plot of CH2M Hill pilot test data for the first 3-foot column and allowing 140 ng/l for 1-methylnaphthalene breakthrough before this, plus 20 ng/l for other compounds). Note that carbon available is (6/9)(40,000 lbs) per the Calgon design and (7.5/10.5)(60,000 lbs) per the CH2M Hill design.

**Note that these carbon life estimates and resulting costs are made on a different basis than those in Calgon's report.

***Carbon lives are based on a 6-foot capacity zone, X/M values from CH2M Hill's bench testing average feed concentrations from CH2M Hill's pilot testing and no credit for any adsorption in the bottom 3-foot MTZ.

The conclusion, then, is that minor adjustments in the noncarcinogen criterion (i.e., keeping the criterion in the range of 100's of ng/l) should have negligible impact on carbon costs. In order to significantly reduce carbon cost (by 25% or more), criteria in the range of 3,000 ng/l or more would be required.

As noted in our April 1983 report, a health-based criterion for noncarcinogenic PAH should be in the range of 100 to 400 ug/l, with 4 ug/l as an very conservative lower bound based on preventing possible organoleptic effects. Since such effects have not been observed at SLP10 and SLP15, a noncarcinogen criterion in the range of 10's of ug/l or higher should be adequate to protect public health. In this case, carbon life would not be controlled by noncarcinogenic PAH, but instead by breakthrough of quinoline and higher molecular weight carcinogens. In this case, carbon life could exceed ten years, based on CH2M Hill's isotherm results.